BROOKHAVEN NATIONAL LABORATORY

1(3), 2, 3(1)... and Counting. Resolving the Neutrino Mass States

BNL Physics Dept. Colloquium, 01/22/2013

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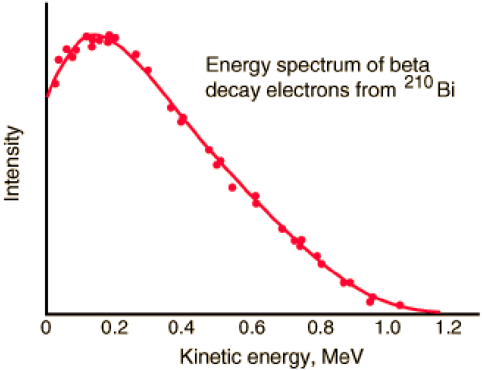
Outline

A BRIEF HISTORY OF THE NEUTRINO

Neutrino Conception

Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



G.J Neary, Proc Phys. Soc., A175, 71 (1940)

Neutrino Conception

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen proposes that a neutrally charged "neutron" with a mass "$<$ 0.01 proton mass" is emitted in beta-decays.

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

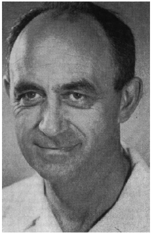
. W. Pauli

Neutrino Conception

1932: James Chadwick discovers the neutron - its too heavy - cant be Pauli's particle

James Chadwick

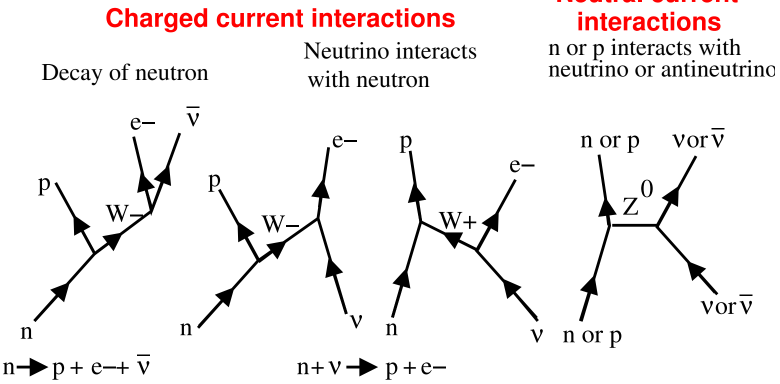
Solvay Conference, Bruxelles 1933: Fermi proposes to name Pauli's particle the "neutrino".



Enrico Fermi

The Theory of Weak Interactions

$\geq$ **1933:** **Development of the theory of weak interactions and beta decay**

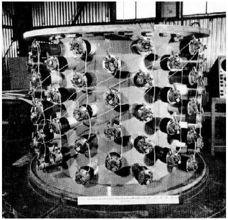


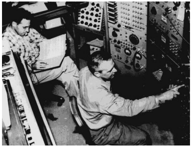
Finding Neutrinos...

1950's: Fred Reines at Los Alamos and Clyde Cowan mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV + T_e^+)
3. $n + {}^{108}Cd \rightarrow {}^{109}Cd* \rightarrow {}^{109}Cd + \gamma$ $(\tau = 5\mu s)$.

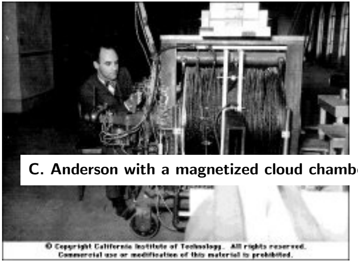




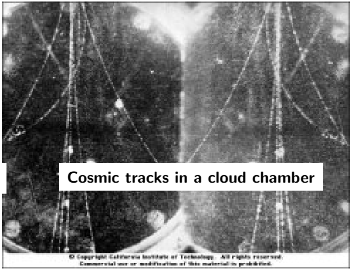
Neutrinos first detected using a nuclear reactor!

The Lepton Family and Flavors

1936: **Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).**



C. Anderson with a magnetized cloud chamber



Cosmic tracks in a cloud chamber

Weak decays of muons: $\mu^{+/-} \rightarrow e^{+/-} + \nu\bar{\nu}$

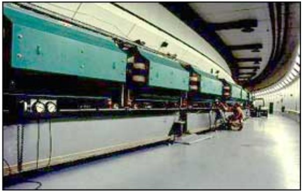
$\text{mass}_{\mu} = 207\ \text{mass}_{e} = 105.7\ \text{MeV}/c^2$, $\tau = 2.2\mu$ sec .

I. I Rabbi (founder of BNL): Who ordered THAT?

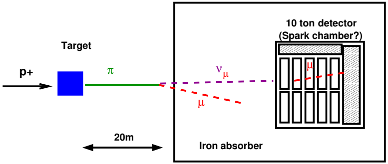
The muon and the electron are *different "flavors" of weakly interacting elementary particles called leptons*. **Neutrinos are neutral leptons. Do ν's have flavor too?**

Neutrinos have Flavors

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu\nu_x$



The AGS



Making ν's

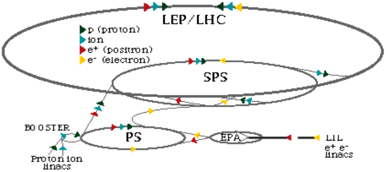
Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

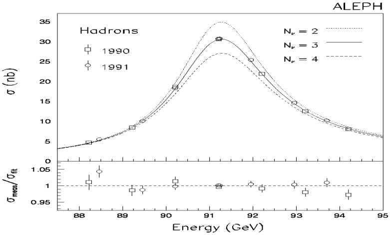
The first accelerator neutrino experiment was at the AGS.

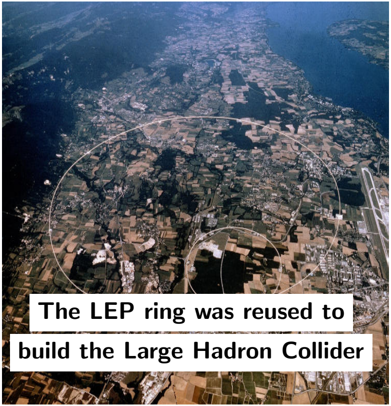
Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- particle colliders. $N_\nu = 2.984 \pm 0.008$

The LEP e^+e^- collider at CERN, Switzerland

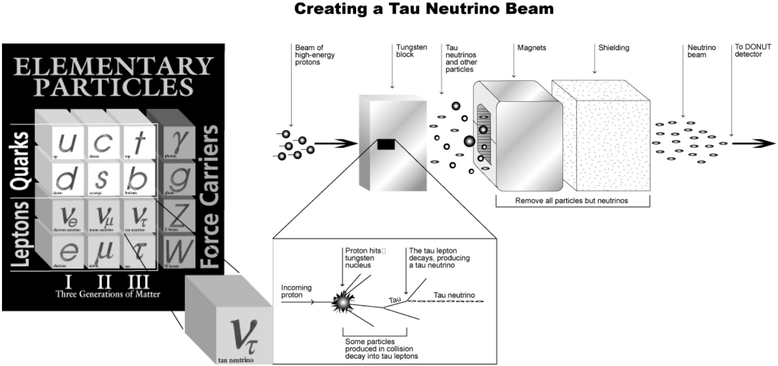






The LEP ring was reused to build the Large Hadron Collider

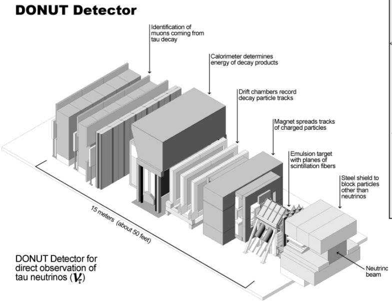
Direct Observation of ν_τ

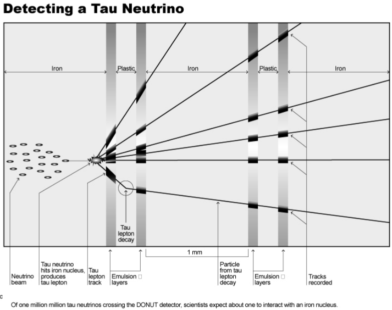


Standard model: 3rd neutrino is the partner of the τ lepton

Direct Observation of ν_τ

July 20, 2000. The DONUT experiment finds evidence for the 3rd neutrino:





NEUTRINO MIXING AND OSCILLATIONS

Neutrino oscillations

1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

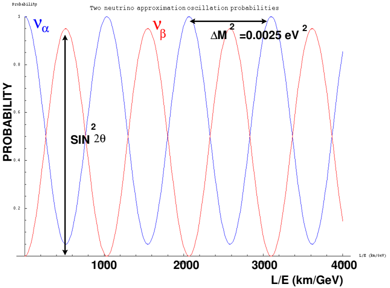
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

Ray Davis

1. $\nu_e^{sun} + {}^{37}\mathrm{CL} \rightarrow e^- + {}^{37}\mathrm{Ar}, \; \tau({}^{37}\mathrm{Ar}) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.

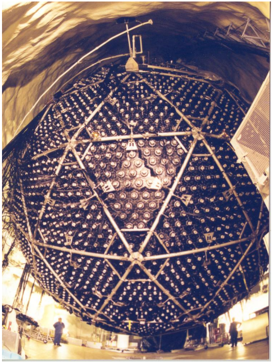
Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Solar ν_e disappearance $\Rightarrow$

first experimental hint of oscillations

SNO Experiment: Solar $\nu_e \rightarrow \nu_x$ Measurments

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:



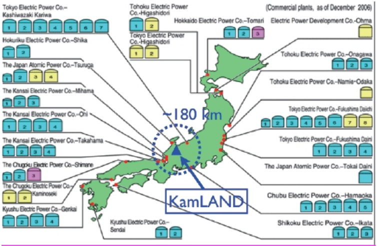
$$1)\ \nu_e + d \rightarrow e^- + p + p\ (CC).$$
$$2)\ \nu_x + d \rightarrow p + n + \nu_x\ (NC).$$
$$3)\ \nu_x + e^- \rightarrow e^- + \nu_x\ (ES).$$

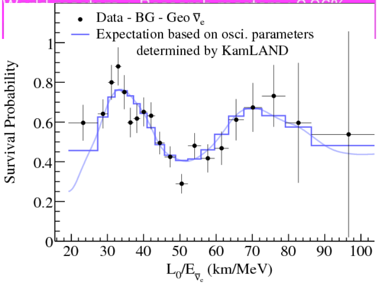
SNO measured:

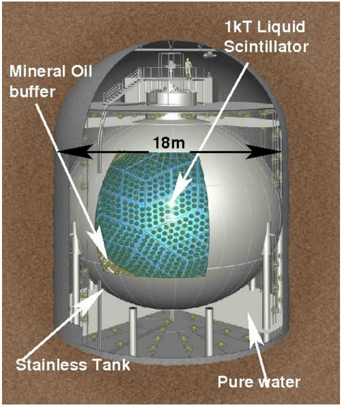
$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6\text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6\text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6\text{cm}^{-2}\text{s}^{-1}$$

All the solar ν's are there but ν_e appears as ν_x!

KamLAND: Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ Oscillations





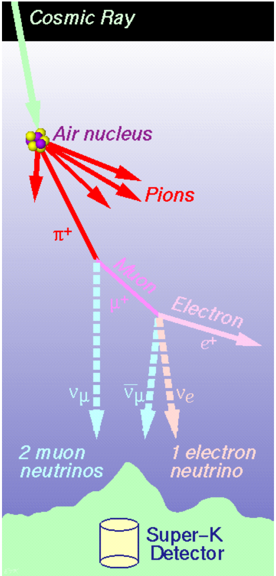


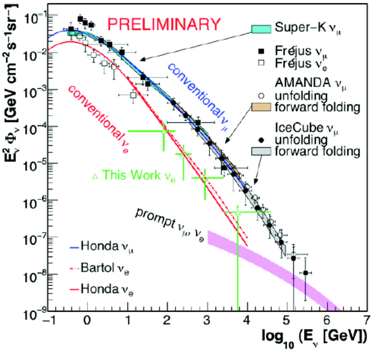
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_x) = \sin^2 2\theta_{solar} \sin^2 \frac{1.27\Delta m^2_{solar} L}{E}$$

$\Leftarrow$ Clear wiggles!

Oscillation scale is $L/E \sim 15{,}000$ km/GeV

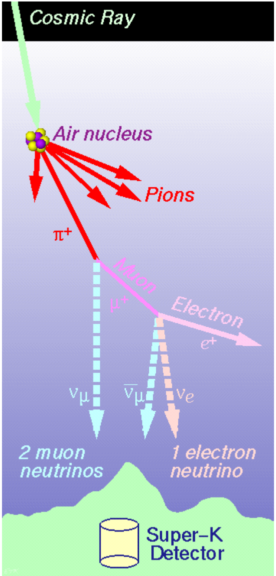
Atmospheric Neutrino Oscillations: $\nu_\mu, \nu_e, \bar{\nu}$

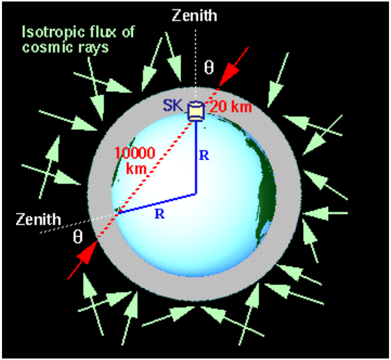




Many decades in E

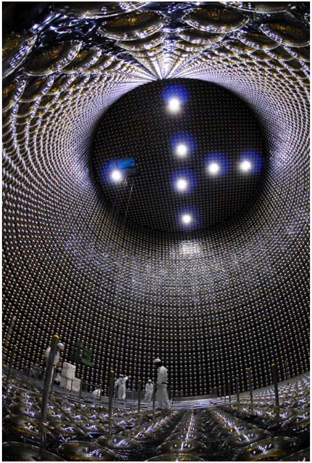
Atmospheric Neutrino Oscillations: $\nu_\mu, \nu_e, \bar{\nu}$





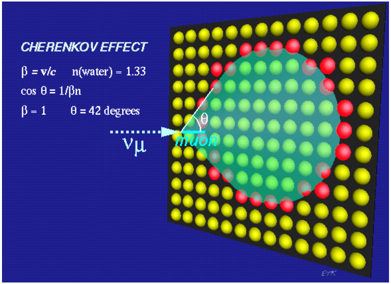
L = 0 to 13,000 km

The Super-Kamiokande Experiment. Kamioka Mine, Japan

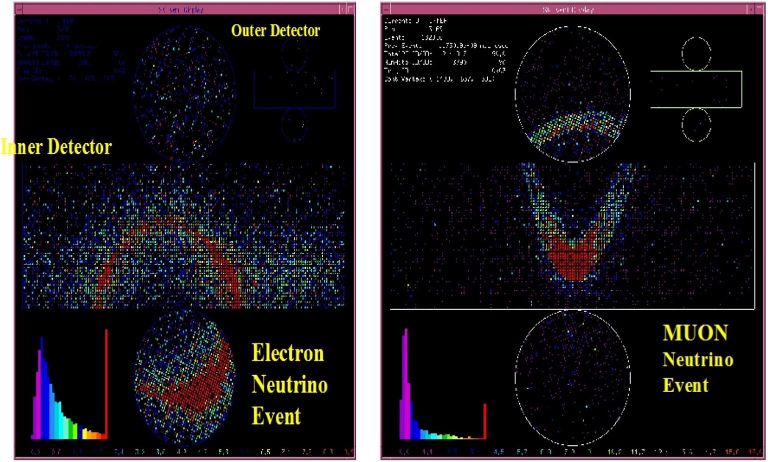


50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

Neutrinos are identified by using CC interaction $\nu_{\mu,e} \rightarrow e^{\pm}, \mu^{\pm}X$. The lepton produces Cherenkov light as it goes through the detector:

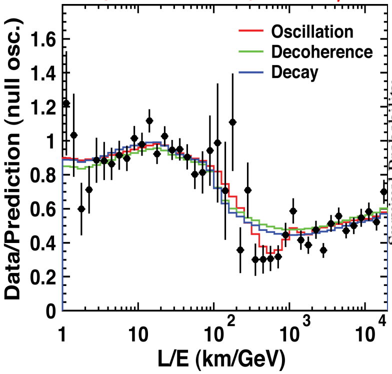


The Super-Kamiokande Experiment. Kamioka Mine, Japan

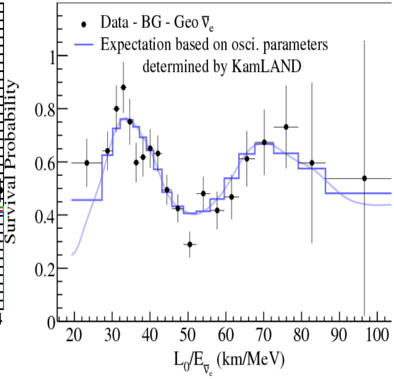


Two Different Mass Scales!

Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E ∼ 500 km/GeV

Global fit 2013:

$$\Delta m^2_{solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2\theta_{solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E ∼ 15,000 km/GeV

More Reactor $\bar{\nu}_e$: The 3rd Mixing Amplitude

1(3), 2, 3(1)... and Counting. Resolving the Neutrino Mass States

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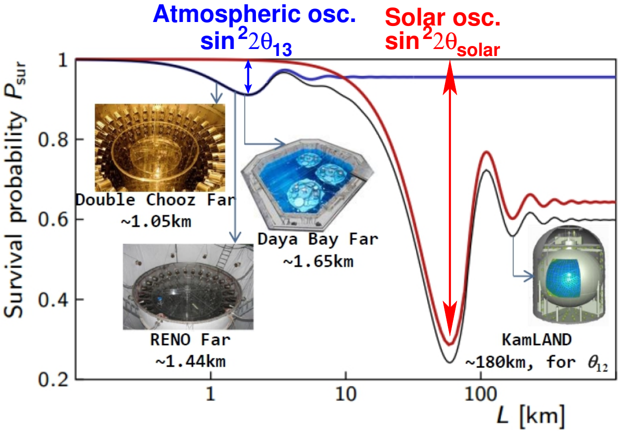
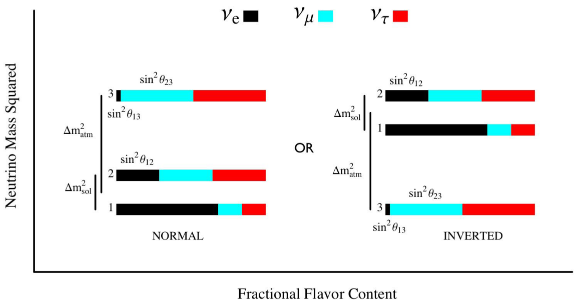


In 2012: Measurement of a 3rd mixing amplitude:

$$\sin^2\theta_{13} = 0.0241 \pm 0.0025$$

Much smaller than $\sin^2\theta_{\text{solar}}$ and $\sin^2\theta_{\text{atm}}$.

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales

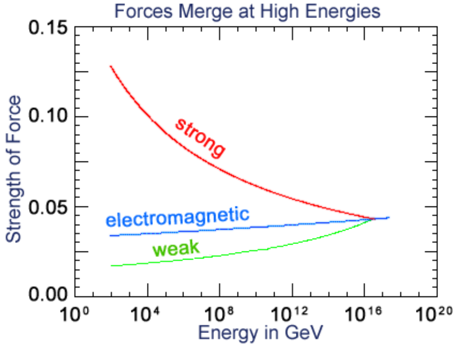


Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12} (solar)	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23} (atm.)	$38 \pm 1^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$
Δm^2_{solar}	$+(7.54 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{atm.}\rvert$	$(2.43^{+0.10}_{-0.06}) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	$-170 \pm 54^\circ$	$67 \pm 5^\circ$

Unknown: Is $m_1 < m_3$ or vice versa?. What is the implication?

Neutrino Masses in the Standard Model

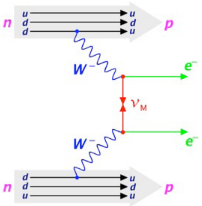
In Grand Unified Theories all 3 forces (strong, electro-magnetic, weak) unify at very high energies:

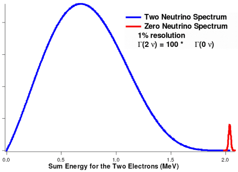


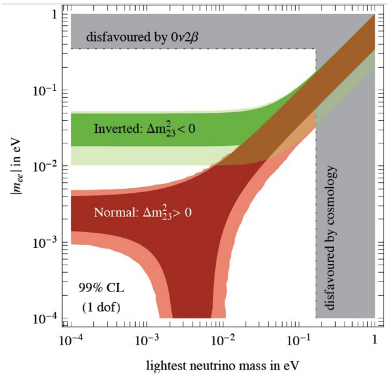
A minimal re-normalizable extension to the Standard Model to account for 3 small left-handed neutrinos introduces 3 additional massive scalar *right-handed* sterile neutrinos of mass $\sim$ M. M $\sim$ GUT scale or M $\sim$ 1 TeV (DARK MATTER?)

See-saw model: Neutrinos are Majorana ($\nu \equiv \bar{\nu}$)

If neutrinos are Majorana, some nuclei can undergo neutrino-less double beta decay:



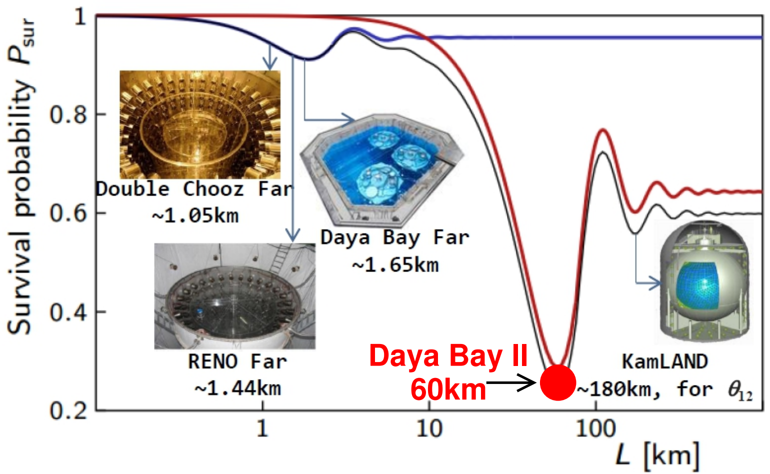




With inverted hierarchy $\Rightarrow$ experimental sensitivity to $0\nu\beta\beta$

Resolving the Mass Ordering: 3 ν Model

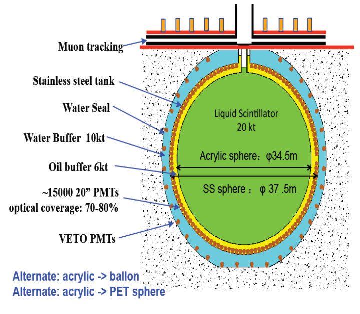
Measuring Sign of Δm^2_{32} with Reactor $\bar{\nu}_e$

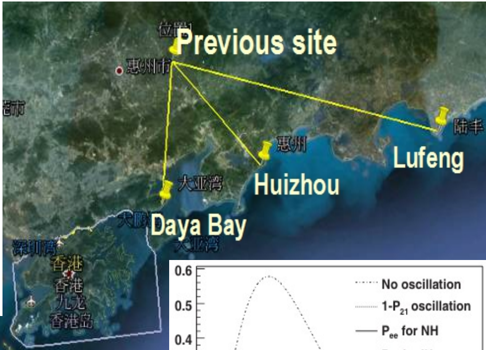


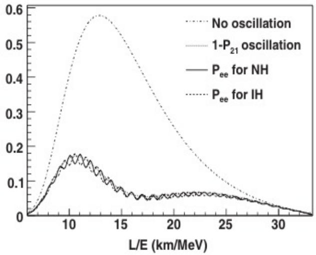
Locate experiment at 60km from reactors - where solar osc. is max

Observe subdominant atm. osc

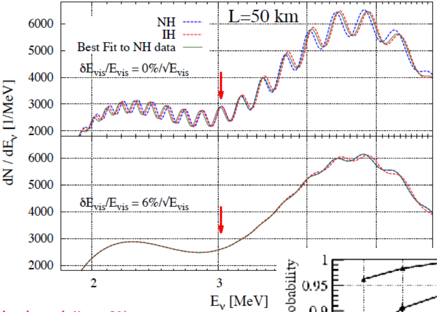
The Daya Bay II Experiment



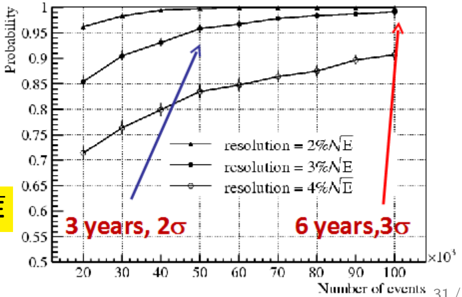




DYBII Challenge 1: Energy Resolution



- Need resolution <3%



Need resolution $\leq 3\%/\sqrt{E}$

DYBII Challenge 2: Energy Non Linearity

- Experimentally measured is essentially the reconstructed energy based on the light collection, which may not be linear to the real energy of the particle
  - Quenching of the scintillator
  - Cherenkov contribution
  - Position dependence
  - Electronics
- With certain non-linearity, the IH could behave like the NH, and vice versa

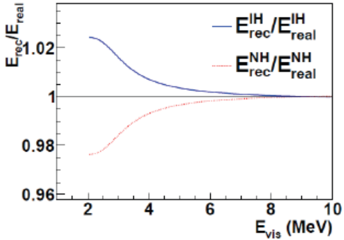
$$\text{IH:} \quad \cos\left(\left(2|\Delta m^2_{32}| - \Delta m^2_\phi(E_{\bar\nu}, L)\right)\frac{L}{E_{real}}\right)$$

$$=$$

$$\text{NH:} \quad \cos\left(\left(2|\Delta' m^2_{32}| + \Delta m^2_\phi(E_{\bar\nu}, L)\right)\frac{L}{E_{rec}}\right)$$

Assuming a non-linearity function

$$E_{rec} = \frac{2|\Delta' m^2_{32}| + \Delta m^2_\phi(E_{\bar\nu}, L)}{2|\Delta m^2_{32}| - \Delta m^2_\phi(E_{\bar\nu}, L)} E_{real} \; .$$

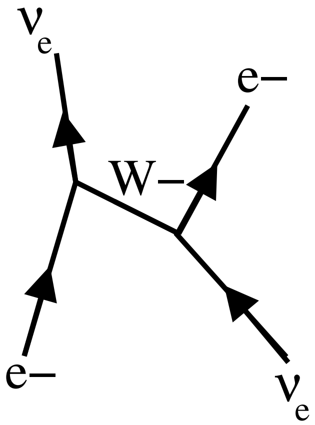


Need to know the non-linearity to <1%

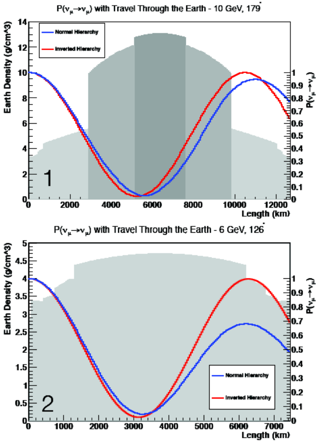
X. Qian et.al. arXiv: 1208.1551

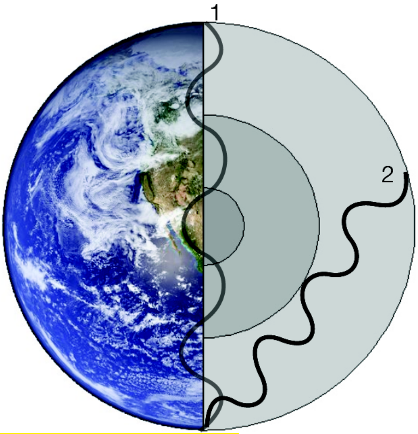
Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter adds a coherent forward scattering amplitude to neutrino oscillation amplitudes. This acts as a refractive index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.



MSW Effect in Atmospheric ν Oscillations

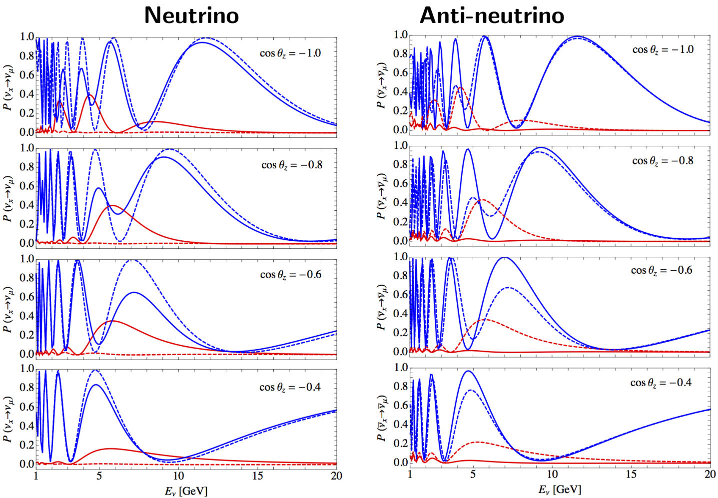




MSW effect sensitive to sign of Δm^2_{32} (atmospheric)

Normal hierarchy (NH): $\Delta m^2_{32} > 0$
Inverted hierarchy (IH): $\Delta m^2_{32} < 0$

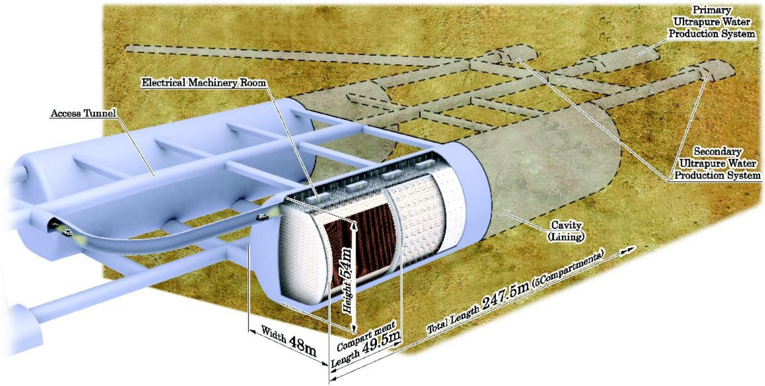
Atm. ν_μ Oscillations and Mass Hierarchy



$\nu_e \to \nu_\mu$ $\nu_\mu \to \nu_\mu$ ___ NH ($\Delta m^2_{atm} > 0$) - - - IH ($\Delta m^2_{atm} < 0$)

Effects are largest in the 3-10 GeV range

The Hyper-Kamiokande Experiment (Proposed)

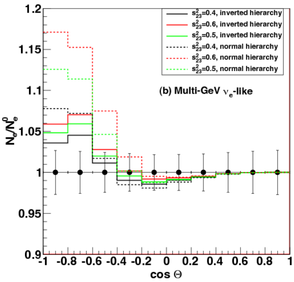


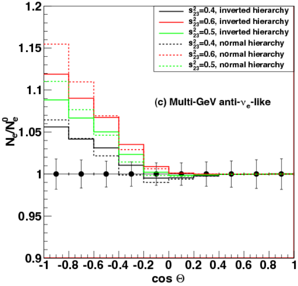
- **Two cylindrical tanks lying side-by-side. Each tank 48 (W) X 54 (H) X 250 (L) m.**
- **The total fiducial mass is 0.99 (0.56) million metric tons $\equiv$ 20 (25) X Super-K.**
- **The inner region viewed by 99,000 20-inch PMTs (20% coverage).**

Hyper-Kamiokande Atmospheric ν and MH

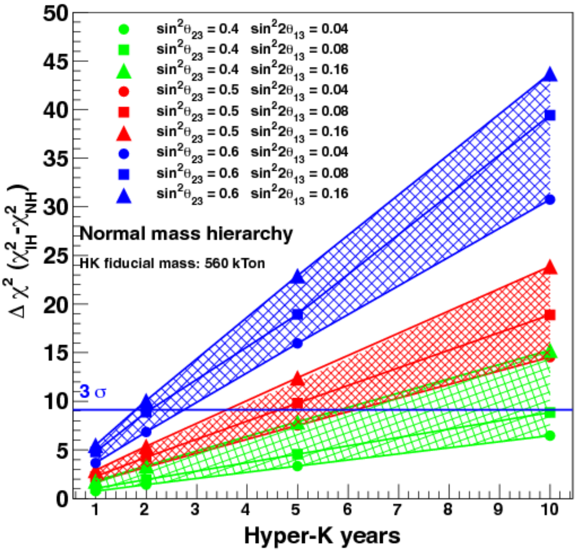
TABLE XII. Expected number of ν_e-like and $\bar{\nu}_e$-like events in 10 Hyper-K years for each interaction component.

	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	NC	Total
ν_e-like sample	15247	2831	3731	4792	26601
- single-ring	6356	1086	1682	1740	10864
- multi-ring	8891	1745	2049	3052	15737
Percentage (%)	57.3	10.6	14.0	18.0	100.0
$\bar{\nu}_e$-like sample	28309	17255	1232	4559	51355
- single-ring	20470	13401	444	2496	36811
- multi-ring	7839	3854	788	2063	14544
Percentage (%)	55.1	33.6	2.4	8.9	100.0



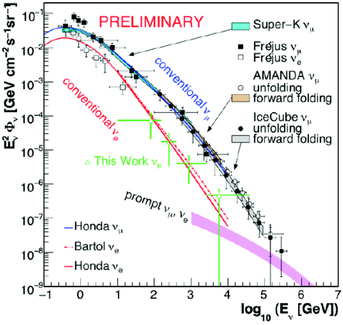


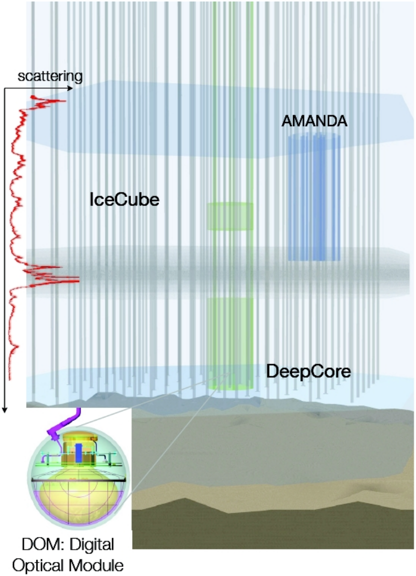
Hyper-Kamiokande Sensitivities



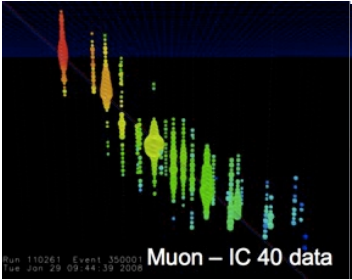
Ice-Cube: 1km^3 ν Detector

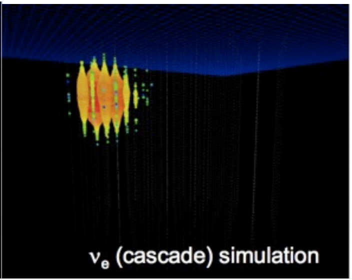
IceCube: 1km ^{3} of Antarctic ice instrumented with 5K DOM. 86 vertical strings with 60 DOMs per string. For $E_\nu > 100$ GeV. DeepCore: 8 special strings with denser DOM spacing $\mathcal{O}(10)$ megaton.

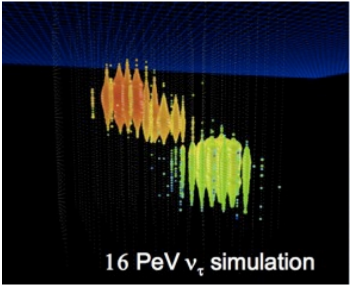




Detecting Neutrinos in IceCube

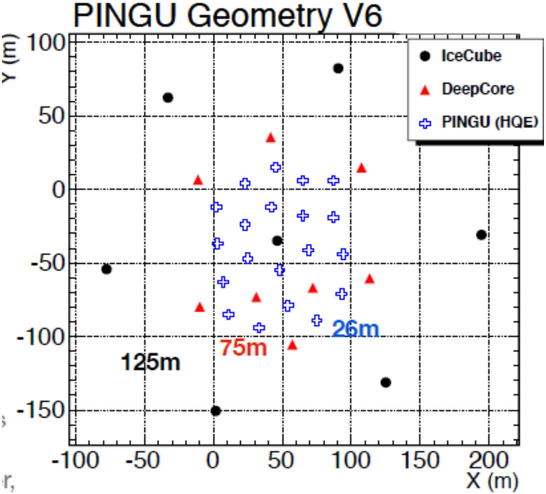






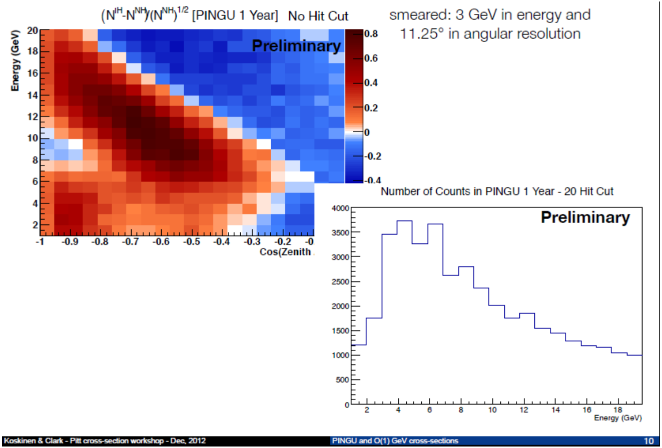
PINGU: A Megaton for GeV Atmospheric ν

Precision IceCube Next Generation Upgrade (PINGU): Proposal to add 20 extra strings added to DeepCore.
Megaton scale for GeV energies.



Sensitivity to the Mass Hierarchy with PINGU

Using $\nu_x \rightarrow \nu_\mu$ oscillations:

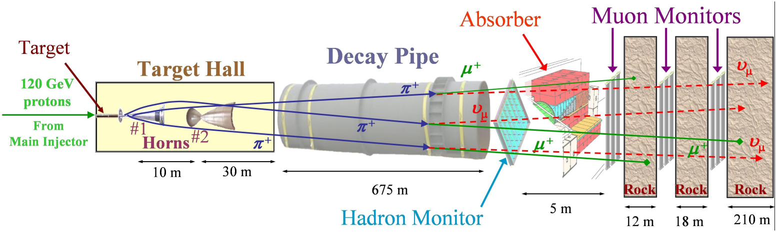


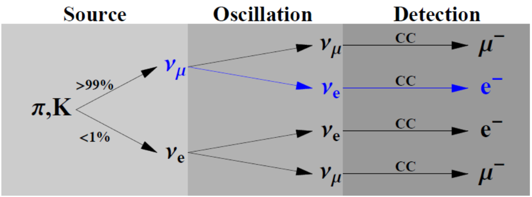
3 GeV energy resolution, 11° angular resolution.

Small effect - difficult to control systematics

Accelerator Neutrino beams at the Intensity Frontier

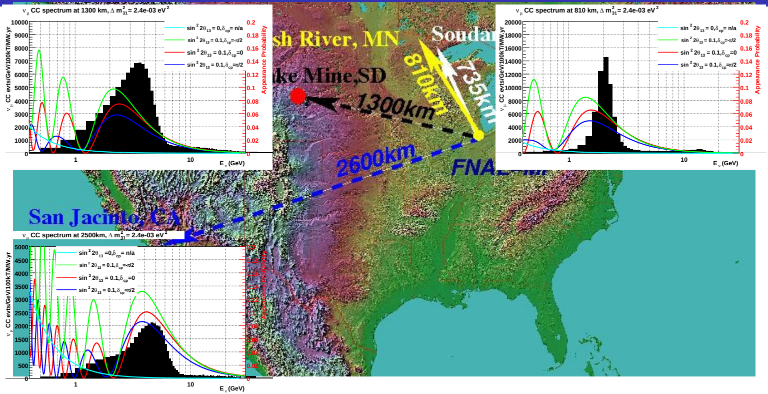
High power conventional neutrino beams (NuMI):





By switching horn currents can select $\nu_\mu/\bar{\nu}_\mu$ beams with $> 90\%$ purity

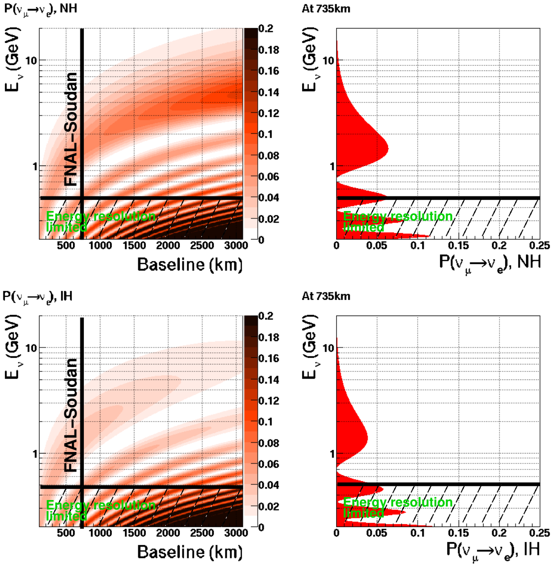
Superbeam Baselines in the U.S.



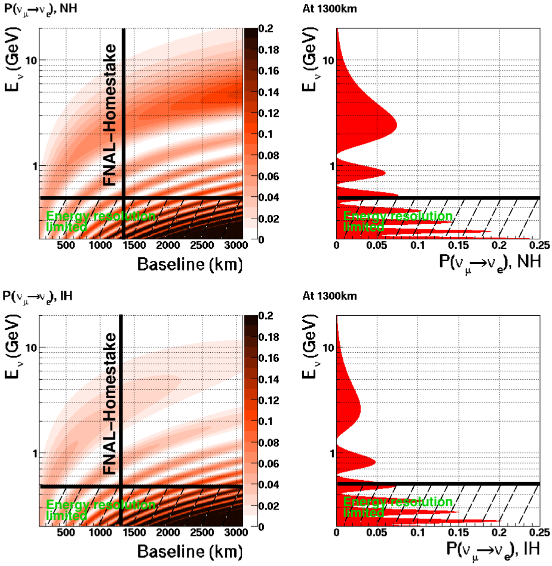
CC event rates per 100kt.MW.yrs (1 MW.yr= 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, NH:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Soudan 735km	73K	49K	15K	820	1500	166
Ash River 810km	18K	7.3K	3.6K	330	710	38
Hmstk 1300km	29K	11K	5.0K	280	1300	130
CA 2500km	11K	2.9K	1.6K	85	760	290

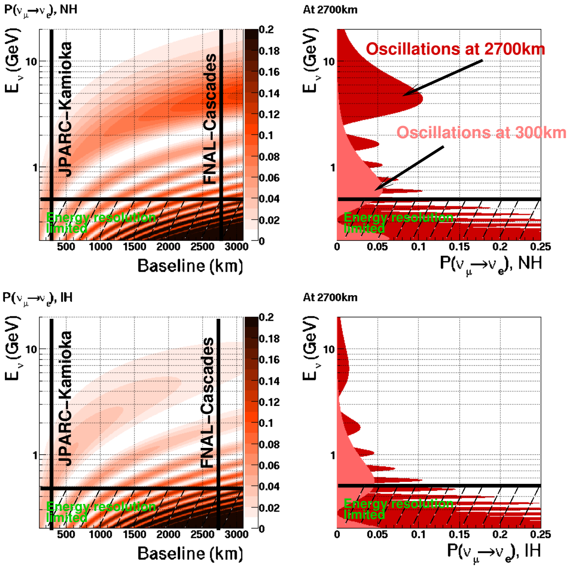
Matter Effect on $\mathbf{P}(\nu_\mu \rightarrow \nu_e)$



Matter Effect on $\mathbf{P}(\nu_\mu \rightarrow \nu_e)$



Matter Effect on $\mathbf{P}(\nu_\mu \to \nu_e)$



Measuring $\nu_\mu/\bar{\nu}_\mu$ Oscillation Asymmetries

The ultimate goal of accelerator neutrino experiments is to search for matter/anti-matter asymmetries by studying $\nu_\mu/\bar{\nu}_\mu$ oscillations using beams with well known spectra and high purity.

The charge-parity (CP) asymmetry is defined as

$$\mathcal{A}_{cp} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\mathcal{A}_{cp} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects}$$

from Z. Parsa, BNL

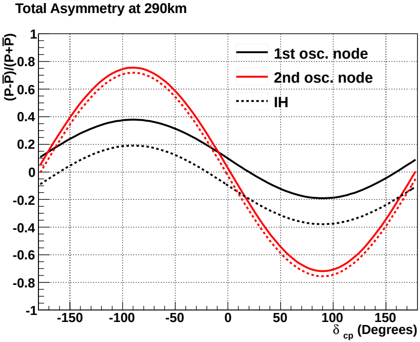
The CP phase δ_{cp} is unknown. CP is violated when $\delta_{cp} \neq 0, \pi$

CP Asymmetries and the Mass Hierarchy

$\nu_\mu \rightarrow \nu_e$ oscillation maxima occur at

$$E^n_\nu(\mathrm{GeV}) = \frac{2.5\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

$L = 290\mathrm{km}$



At short baselines, irreducible degeneracies with MH,δ_{cp}

CP Asymmetries and the Mass Hierarchy

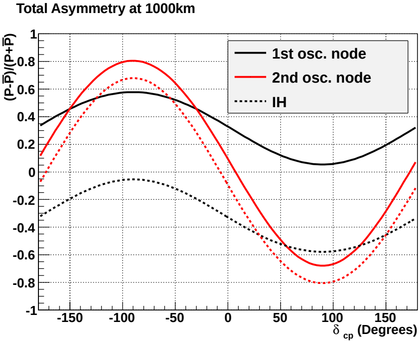
1(3), 2, 3(1)... and Counting. Resolving the Neutrino Mass States

Mary Bishai
Brookhaven National Laboratory

$\nu_\mu \to \nu_e$ oscillation maxima occur at

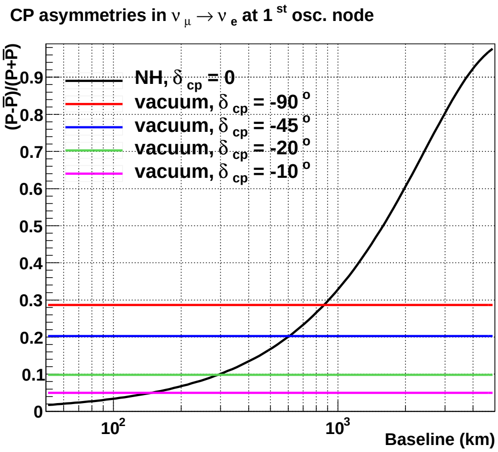
$$E^n_\nu(\mathrm{GeV}) = \frac{2.5\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

$L = 1000$km



A baseline $>$ 1000km is needed separate MH from δ_{cp}

Matter Asymmetries and Baselines



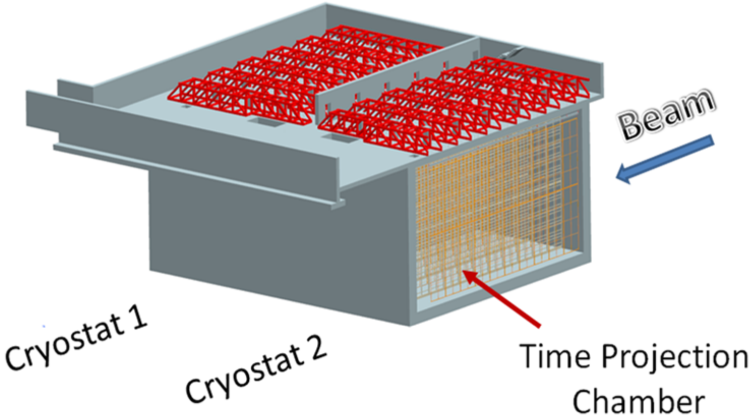
Impact of the mass hierarchy on asymmetry is very large in long baseline experiments

The Long Baseline Neutrino Experiment (LBNE) - Proposed

Massive Liquid Argon Time-Projection-Chamber

Accelerator $\nu_\mu \rightarrow \nu_e$ oscillations are subdominant due to small value of $\sin^2 2\theta_{13}$ compared to $\sin^2 2\theta_{atm}$. Excellent particle ID is needed:

10 kT Liquid Argon TPC for the LBNE Experiment:

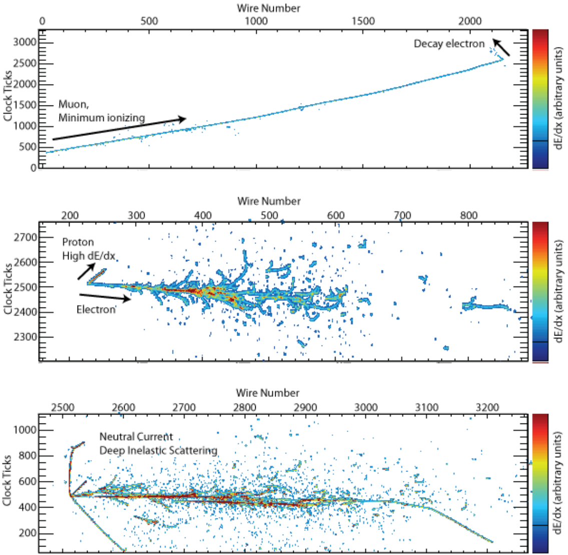


Reconstructing ν Events in a LAr-TPC

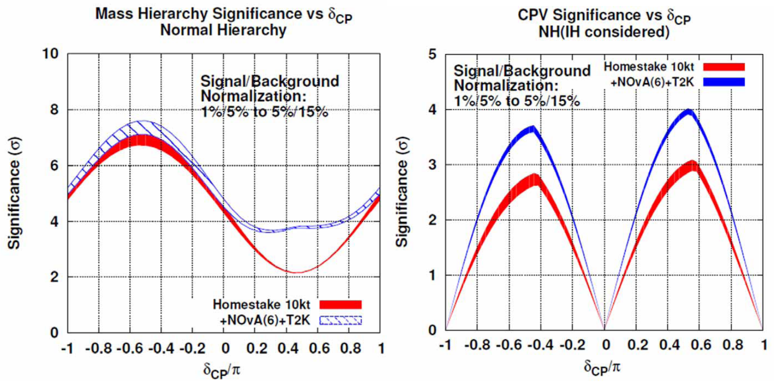
ν_μ CC

ν_e CC

ν_x NC



Mass Hierarchy/CP Violation Sensitivity



The mass hierarchy can be cleanly determined using LBNE combined with current accelerator long-baseline experiments

Mary Bishai
Brookhaven National Laboratory

SUMMARY AND CONCLUSIONS

Summary

The 3 flavor framework for neutrino oscillations is well established

- **Experiments have identified 2 very different mass scales and 3 mixing amplitudes. The mass ordering (hierarchy) of the 1 and 3 mass states is still unknown.**
- **The simplest extension to the Standard Model to allow non-zero neutrino mass favors Majorana neutrinos ($\nu \equiv \bar{\nu}$) and could provide a link to the GUT scale - or a dark matter candidate!**
- **An inverted hierarchy ($m_1 > m_3$) would make determing whether neutrinos are Majorana experimentally feasible.**
- **Determing the mass hierarchy is experimentally HARD!! . It requires very ambitious next generation neutrino experiments that will not be ready till the end of the decade.**
- **The measurement of the hierachy using the matter effect in long baseline accelerator $\nu_\mu \rightarrow \nu_e$ is the most effective technique**
- **It is NOT necessary to know MH to measure CP violation . Baselines of > 1000 km are needed to cleanly separate CP violating effects from matter effects.**

Thank you